

BISTABLE NEMATIC LIQUID CRYSTAL DEVICE

FIELD OF THE INVENTION

- 5 This invention relates to bistable nematic liquid crystal devices.

BACKGROUND OF THE INVENTION

- 10 Liquid crystal devices typically comprise a pair of opposed, spaced-apart translucent cell walls with liquid crystal ("LC") material between them. The cell walls have transparent electrode patterns for applying fields to align the LC material.
- 15 Liquid crystal (LC) materials are rod-like or lath-like molecules which have different optical properties along their long and short axes. The molecules exhibit some long range order so that locally they tend to adopt similar orientations to their neighbours. The local orientation of the long axes of the molecules is referred to as the director. When the director is orientated perpendicular to the plane of the cell walls, this is referred to as homeotropic alignment.
- 20 Alignment of the director along the plane of the cell walls or at an angle to the plane of the cell walls is referred to respectively as planar homogeneous and tilted homogeneous alignment.
- 25 There are three types of LC materials: nematic, cholesteric (chiral nematic), and smectic. The present invention concerns devices using nematic LC materials, which may optionally be chiral or chirally doped.
- 30 Typical LC displays which employ nematic LC materials
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are monostable, application of an electric field causing the LC molecules to align in an "on" state, and removal of the electric field permitting the LC molecules to revert to a pre-determined "off" state.

5 Examples of such monostable modes are twisted nematic (TN), supertwisted nematic (STN) and hybrid aligned nematic (HAN) modes. Each "on" pixel must be maintained above an electric field threshold, which can cause problems in the matrix addressing of complex
10 displays. These problems can be overcome by driving each pixel by a thin film transistor (TFT), but manufacturing large area TFT arrays is difficult and adds to manufacturing costs.

15 A number of bistable LC devices have been proposed in which a nematic LC has more than one stable orientation of the director, and can be switched between two stable states when addressed by suitable waveforms.

20 US patent number 4,333,708 discloses a multistable LC device in which switching between stable configurations is by the movement of disclinations in response to electric fields.

25 In WO 91/11747 and WO 92/00546 it is proposed to provide a bistable surface by careful control of the thickness and evaporation of SiO coatings. A first stable planar orientation of the director could be obtained, and a second stable orientation in which the
30 director is at an azimuthal angle (in the plane of the surface) of 90° to the first orientation in the plane of the surface, and tilted by around 30°.

It has been proposed, in GB 2,286,467, to achieve an
35 azimuthal bistable surface by using a birefracting surface

in which the director is planar to the surface and two surface orientations are stabilised by precise control of the dimensions of the grating.

5 In "Mechanically Bistable Liquid-Crystal Display Structures", R N Thurston et al, IEEE Trans. on Elec. Devices, Vol. ED-27, No. 11, Nov. 1980, there are described two bistable nematic LC modes which are called "vertical-horizontal" and "horizontal-
10 horizontal". In the vertical-horizontal mode, both cell walls are treated to give a roughly 45° tilt which permits the directors to be switched between two states in a plane which is perpendicular to the major surfaces of the device. In the horizontal-horizontal mode, the
15 director is switchable between two angles in a plane parallel to the major surfaces of the device.

WO 97/14990 and WO 99/34251 describe the use of a monograting surface with a homeotropic local director,
20 which has two stable states with different tilt angles within the same azimuthal plane. The homeotropic alignment is achieved by creating the monograting in a layer of material which causes spontaneous homeotropic orientation or, more practically, by coating the
25 grating surface with a homeotropic inducing alignment agent such as lecithin.

We have now found that a bistable nematic LC device may be constructed using an array of features which are
30 shaped so as to permit the director to adopt either of two tilt angles in substantially the same azimuthal direction. The cell can be switched between the two tilt states by an applied electric field to display information which can persist after the removal of the
35 field.

The term "azimuthal direction" is used herein as follows. Let the walls of a cell lie in the x,y plane, so that the normal to the cell walls is the z axis.

- 5 Two tilt angles in the same azimuthal direction means two different director orientations in the same x,z plane, where x is taken as the projection of the director onto the x,y plane.

10 SUMMARY OF THE INVENTION

According to an aspect of the present invention there is provided a bistable nematic liquid crystal device comprising:

- 15 a first cell wall and a second cell wall enclosing a layer of nematic liquid crystal material;
electrodes for applying an electric field across at least some of the liquid crystal material;
a surface alignment on the inner surface of at least
20 the first cell wall providing alignment to the liquid crystal molecules;
wherein the surface alignment comprises an array of features which have a shape and/or orientation to induce the director adjacent the features to adopt two
25 different tilt angles in substantially the same azimuthal direction;
the arrangement being such that two stable liquid crystal molecular configurations can exist after suitable electrical signals have been applied to the
30 electrodes.

We have surprisingly found that the orientation of the director is induced by the geometry of the features, rather than by the array or lattice.

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In a preferred embodiment, the features comprise a plurality of upstanding posts. The features could also comprise mounds, pyramids, domes, walls and other promontories which are shaped or orientated to permit the LC director to adopt one of two different tilt angles in substantially the same azimuthal direction. The invention will be described for convenience hereinafter with respect to posts; however it is to be understood that the invention is not limited to this embodiment. The posts may have substantially straight sides, either normal or tilted with respect to the major planes of the device, or the posts may have curved or irregular surface shape or configuration.

The director tends to align locally in an orientation which depends on the specific shape of the post. For an array of square posts, the director may align along either of the two diagonals of the posts. If another shape is chosen, then there may be more than two azimuthal directions, or just one. For example an equilateral triangular post can induce three directions substantially along the angle bisectors. An oval or diamond shape, with one axis longer than the others, may induce a single local director orientation which defines the azimuthal direction. It will be appreciated that such an orientation can be induced by a very wide range of post shapes. Moreover, by tilting a square post along one of its diagonals it is possible to favour one direction over another. Similarly, tilting of a cylindrical post can induce an alignment in the tilt direction.

Because the local director orientation is determined by the geometry of the posts, the array need not be a regular array. In a preferred embodiment, the posts

are arranged in a random or pseudorandom array instead of in a regular lattice. This arrangement has the benefit of eliminating diffraction colours which may result from the use of regular structures. Such an array can act as a diffuser, which may remove the need for an external diffuser in some displays. Of course, if a diffraction colour is desired in the display, the array may be made regular, and the posts may be spaced at intervals which produce the desired interference effect. Thus, the structure may be separately optimised to give the required alignment and also to mitigate or enhance the optical effect that results from a textured surface.

The posts may be formed by any suitable means; for example by photolithography, embossing, casting, injection moulding, or transfer from a carrier layer. It is not necessary to treat the posts with a coating to induce homeotropic alignment.

In one embodiment some degree of twist is induced in the LC director, which may improve the optical characteristics of the device. The twist may be induced by using LC materials which are chiral or which have been chirally doped. Additionally, or alternatively, twist may be induced by treating the inner surface of the second cell wall to induce a planar or tilted planar alignment which is at a non-zero angle with respect to the azimuthal direction induced by the features on the first cell wall.

The second cell wall is preferably treated to induce a homeotropic local alignment, which may be achieved by well known surface treatments such as lecithin or a chrome complex. In this mode, it is also desirable to

use a nematic LC of negative dielectric anisotropy, to facilitate switching from a lower energy high tilt state to a higher energy low tilt state. However, we have found that a planar alignment also permits

5 bistable switching between optically distinct states. The planar alignment was achieved using a monograting on the second surface, with the grooves aligned parallel with the preferred direction on the other surface. Nematic liquid crystals of positive

10 dielectric anisotropy can also be used. For convenience, the invention will be described hereinafter with reference to a homeotropic alignment on the second cell wall, but it is to be understood that the invention is not limited to this embodiment.

15 In use, the device will be provided with means for distinguishing between switched states of the liquid crystal material. For example a polariser and an analyser may be mounted either side of the LC cell in a

20 manner well known to those skilled in the art of LCD manufacture. Between crossed polarisers, the high tilt state appears dark and the low tilt state appears bright because of its increased birefringence. Alternatively, a pleochroic dye may be dissolved in the

25 LC material, and a single polariser may optionally be mounted on the cell. However, the device may be manufactured and sold without polarisers or other distinguishing means.

30 The posts may be of any height which permits the LC material to adopt two different tilt states. These heights will differ with different LC materials and cell characteristics. A preferred height range is 0.5 to 5 μm , notably 0.9 to 1.3 μm (for a cell gap of about

35 3 μm . If the posts are too low, planar orientation

will tend to predominate, whilst if the posts are too tall, a high tilt or homeotropic orientation will predominate.

- 5 The posts may be of any convenient width (size). A preferred width range is 0.2 to 3 μm . The posts are preferably spaced apart from each other by between 0.1 and 5 μm .
- 10 The posts may be provided on one cell wall only, or they may optionally be provided on both cell walls.
- The alignment posts may optionally be interspersed with taller posts for providing cell spacing.
- 15 The cell walls may be formed from glass, or from a rigid or non-rigid plastics material, for example PES, PET, PEEK, or polyamide.
- 20 It is preferred that one electrode structure (typically a transparent conductor such as indium tin oxide) is provided on the inner surface of each cell wall in known manner. For example, the first cell wall may be provided with a plurality of "row" electrodes and the
- 25 second cell wall may be provided with a plurality of "column" electrodes. However, it would also be possible to provided planar (interdigitated) electrode structures on one wall only, preferably the first cell wall.
- 30 The inner surface of the second cell wall could have low surface energy so that it exhibits little or no tendency to cause any particular type of alignment, so that the alignment of the director is determined
- 35 essentially by the features on the first cell wall.

However, it is preferred that the inner surface of the second cell wall is provided with a surface alignment to induce a desired alignment of the local director. This alignment may be homeotropic, planar or tilted.

- 5 The alignment may be provided by an array of features of suitable shape and/or orientation, or by conventional means, for example rubbing, photoalignment, a monograting, or by treating the surface of the wall with an agent to induce homeotropic
10 alignment.

- The shape and/or orientation of the features is preferably such as to favour only one azimuthal director orientation adjacent the features. The orientation may
15 be the same for each feature, or the orientation may vary from feature to feature so as to give a scattering effect in one of the two states.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be further described by way of example, with reference to the following drawings in
5 which:

Figure 1 is a schematic cross section through a single post and the surrounding LC in accordance with the present invention. The cross section is
10 in the x,y plane. The ellipses represent the LC molecules with the long axis corresponding to the local director;

Figure 2 shows schematic views of a cross section through a single post and the surrounding LC of a
15 bistable nematic device in accordance with one aspect of the present invention, along one of the diagonals of a post, in different states;

Figure 3 shows schematic views of a cross section through a single post and the surrounding LC of a
20 bistable nematic device in accordance with another aspect of the present invention, along one of the diagonals of a post, in different states;

Figure 4 is a plan view of a unit cell of a device
25 in accordance with the present invention, having posts in a pseudorandom array;

Figures 5 and 6 show change in transmission of an
30 experimental cell in accordance with the invention, as a function of pulse length and amplitude, for switching between two states;

Figures 7 to 10 are SEM photomicrographs of arrays
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of posts used in the manufacture of liquid crystal devices in accordance with the invention; and

5 Figures 11 and 12 are views of different arrays of features of devices in accordance with further embodiments of the invention

DETAILED DESCRIPTION

10 The bistable nematic cell shown schematically in Figure 2 comprises a first cell wall 2 and a second cell wall 4 which enclose a layer of nematic LC material of negative dielectric anisotropy. The molecules of the LC are represented as ellipses, with the long axis
15 indicating the local director. The inner surface of each cell wall is provided with a transparent electrode pattern, for example row electrodes 12 on the first cell wall 2 and column electrodes 14 on the second cell wall 4, in a known manner.

20 The inner surface of the first cell wall 2 is textured with a regular array of square posts 10, and the inner surface of the second cell wall 4 is flat. The posts 10 are approximately 1 μm high and the cell gap is
25 typically 3 μm . The flat surface is treated to give homeotropic alignment. The posts are not homeotropically treated.

Such an array of square posts has two preferred
30 alignment directions in the azimuthal plane. These are along the two diagonals of the post. Figure 1 shows a cross-section through a post with the LC distorted around it, from one corner to the diagonally opposite one. This alignment around the post then tends to seed
35 the alignment of the LC above the post such that the

average orientation is also along that diagonal.

By tilting the posts along one of the diagonals (Figure 2) it is possible to favour that alignment direction. Through computer simulation of this geometry we found that although there is only one azimuthal alignment direction there are in fact two states with similar energies but which differ in how much the LC tilts. Figure 2 is a schematic of the two states. In one state (shown on the left of Figure 2) the LC is highly tilted, and in the other it is planar around the posts. The exact nature of the LC orientation depends on the details of the structure, but for a range of parameters there are two distinct states with different magnitudes of tilt away from the cell normal. The two states may be distinguished by viewing through a polariser 8 and an analyser 6. The low tilt state has high birefringence and the high tilt state has low birefringence. Tilting the posts sufficiently along the diagonal also serves to eliminate reverse tilt states. Preferably the posts are tilted by at least 5°, depending on the nature of the LC and the cell gap.

Without limiting the scope of the invention in any way, we think that the two states may arise because of the way in which the LC is deformed by the post. Flowing around a post causes regions of high energy density at the leading and trailing edges of the post where there is a sharp change in direction. This can be seen in Figure 1 at the bottom left and top right corners of the post. This energy density is reduced if the LC molecules are tilted because there is a less severe direction change. This is clear in the limit of the molecules being homeotropic throughout the cell. In that case there is no region of high distortion at the

post edges. In the higher tilt state this deformation energy is therefore reduced, but at the expense of a higher bend/splay deformation energy at the base of the posts. The LC in contact with the flat surface between
5 posts is untilted but undergoes a sharp change of direction as it adopts the tilt around the post.

In the low tilt state the energy is balanced in the opposite sense, with the high deformation around the leading and trailing edges of the post being partially
10 balanced by the lack of the bend/splay deformation at the base of the post because the tilt is uniform around the post. Our computer simulations suggest that, for the current configuration, the higher tilt state is the lower energy state.

15 This is supported by the results of computer simulation and in actual cells. When viewed at an appropriate angle between crossed polarisers the cells always cool into the darker of the two states. From Figure 2 it would appear that the high tilt state will have lower
20 birefringence and therefore appear darker than the low tilt state. The exact amount of tilt in the high tilt state will be a function of the elastic constants of the LC material and the planar anchoring energy of the post material.

25 Referring now to Figure 3, there is shown a computer-generated model of LC alignment around a square post similar to that shown in Figure 2, but with the inner surface of the second cell wall treated to give planar
30 alignment. In the state shown in the left in Figure 3, the local director is highly tilted, and in the other it is planar around the posts. As with the cell of Figure 2, switching between the two states is achieved by the application of suitable electrical signals.

Figure 4 shows a pseudorandom array of posts for an alternative embodiment of the invention, which provides bistable switching without interference effects. Each square post is about $0.8 \times 0.8 \mu\text{m}$, and the pseudorandom array has a repeat distance of $56 \mu\text{m}$.

Cell Manufacture

10 A clean glass substrate 2 coated with Indium Tin Oxide (ITO) was taken and electrode patterns 12 were formed using conventional lithographic and wet etch procedures. The substrate was spin-coated with a suitable photoresist (Shipley S1813) to a final
15 thickness of $1.3 \mu\text{m}$.

A photomask (Compugraphics International PLC) with an array of suitably-dimensioned square opaque regions in a square array, was brought into hard contact with the
20 substrate and a suitable UV source was used to expose the photoresist for 10 s at $\sim 100 \text{ mW/cm}^2$. The substrate was developed using Microposit Developer diluted 1:1 with deionised water for approximately 20 s and rinsed dry. The substrate was flood exposed using a 365 nm UV
25 source for 3 minutes at 30 mW/cm^2 , and hardbaked at 85°C for 12 hours. The substrate was then deep UV cured using a 254 nm UV source at $\sim 50 \text{ mW/cm}^2$ for 1 hour. By exposing through the mask using a UV source at an offset angle to the normal to the plane of the cell
30 wall, tilted posts could be produced. The tilt angle (or blaze angle) is related to the offset angle by Snell's law. Exposure to the developer will also affect the shape of the posts.

35 A second clean ITO substrate 4 with electrode patterns

14 was taken and treated to give a homeotropic alignment of the liquid crystal using a stearyl-carboxy-chromium complex, in a known manner.

5 An LC test cell was formed by bringing the substrates together using suitable spacer beads (Micropearl) contained in UV curing glue (Norland Optical Adhesives N73) around the periphery of the substrates 2, 4, and cured using 365 nm UV source. The cell was capillary
10 filled with a nematic liquid crystal mixture (Merck ZLI 4788-000). Methods of spacing, assembling and filling LC cells are well known to those skilled in the art of LCD manufacture, and such conventional methods may also be used in the spacing, assembling and filling of
15 devices in accordance with the present invention.

Experimental Results

Figures 5 and 6 show the switching response of a
20 bistable cell recorded at 42.5°C. The cell had the following characteristics:

spacing: 3 μm
post height: 1.4 μm
25 gap between posts: 0.7 μm
offset angle: 12°
LC: ZLI 4788-000 (Merck) doped with 3% N65 (Norland).

It was found that adding a small quantity of surfactant
30 oligomer to the LC improved the switching. It is known that switching in conventional LC devices can be improved by addition of surfactant oligomers to the LC. See, for example, G P Bryan-Brown, E L Wood and I C Sage, *Nature* Vol. 399 p338 1999. We doped the LC with
35 N65 UV-curable glue (from Norland) and cured it while

in the isotropic phase. The doped LC was then mass filtered to remove the longer chain lengths. We found that adding 3% by weight of N65 to the LC was optimum.

5 DC balanced monopolar pulses were applied to the cell and the effect on the transmission was recorded. Each test pulse was of an amplitude V and a duration τ , and was followed by another pulse of opposite polarity but with an amplitude about 5% of V , but a duration 20
10 times longer. The second pulse was too small to cause switching but did prevent a build up of charge in the cell after many test pulses. Figures 5 and 6 show the change in transmission as a function of the pulse length and amplitude. Figure 5 shows results for
15 switching from the high energy state to the low energy state, and Figure 6 shows results for switching in the opposite direction. Black indicates that the transmission had changed so that the cell is switched. White indicates no change in transmission so that no
20 switching has occurred.

Switching from the high energy state to the low energy state is generally sign independent indicating that in this direction switching is taking place via the
25 dielectric anisotropy. Switching in the other direction is sign dependent indicating that the switching is mediated by a linear electro-optic effect. We believe this is likely to be the flexoelectric effect. In Figure 5, the non-switching region
30 coincides with the switching region in Figure 6. This suggests that switching from the high energy state to the low energy state is impeded by the flexoelectric effect.

35 In a series of further experiments we have varied the

cell parameters to go some way towards optimising the switching characteristics of the device. A preferred cell structure is: cell gap 3 μm ; post size 1 μm ; offset angle 5° along one of the diagonals of the post;
5 1.1 μm coating of s1813; N65 initial concentration 3%.

SEM Studies of Post Arrays

SEMs of experimental post arrays formed using masks
10 with square holes are shown in Figures 7 to 10. The posts in Figures 7 and 8 were formed using 0.7 μm square opaque regions 90% s1813, and a 5° offset angle. The alert reader will note that the 0.7 μm "square" posts are not very square, having considerably rounded
15 tops. The bases of the posts are much less rounded than the tops of the posts. This is consistent with the rounding being due to the development process. The tops of the posts are exposed to the developer for a longer time than the bases. They are therefore more
20 susceptible to attack. Even the unexposed resist that makes up the posts will have some finite solubility in the resist, and the effect will be to attack sharp features such as corners first. Larger posts show much less rounding off; for example Figure 9 shows some 2 μm
25 posts.

The other feature that is particularly obvious in Figures 7 and 8 is the ripples up the sides of the posts. It is thought that this is due to interference
30 from light reflected from the substrate, since these arrays of posts were exposed by a 442 nm laser beam. The effect is much less obvious in gratings exposed with a mask aligner which uses a UV lamp that emits multiple wavelengths which are incoherent, reducing the effect of
35 any interference. These ripples do not seem to affect

the switching.

Another interesting feature from the SEMs is the absence of overhangs in even the most blazed posts, for example
5 Figure 10 shows some $0.7 \mu\text{m}$ posts exposed at 30 degrees without significant overhang. Again we think any overhangs would be very susceptible to attack by the developer.

10 Computer simulations with rounded posts

We have generated computer models that look very similar to the $0.7 \mu\text{m}$ rounded posts of Figures 7 and 8. Even though the posts are far from the idealised square posts
15 that we had used in previous simulations, these more realistic posts still give the same states, aligned along the blazed diagonals, but with two different magnitudes of tilt. The energies of the two states are slightly lower than before, but the tilted state still
20 has the lowest energy. It seems that it is not essential to have sharp edges to the posts. The two states are believed to arise because of the way that the LC is distorted around a post (as previously discussed). This will be true whatever the shape of the cross-
25 section of the post. Even cylindrical posts should give the same two zenithal alignments. However, with cylindrical symmetry there is nothing to fix the azimuthal alignment of the LC - all directions will be degenerate. The posts need to have some asymmetry to
30 lift this degeneracy. This could be for example an elliptical, diamond or square cross section with a small amount of blaze. Examples of elliptical posts are given in Figure 11, those on the right hand side having an overhang. Referring now to Figure 12, examples are
35 shown wherein the shape and/or orientation of the posts

is such as to favour only one azimuthal director orientation adjacent the posts. In the embodiment on the left side of Figure 12, this orientation varies from post to post so as to give a scattering effect in one of
5 the two states. In the embodiment shown on the right side of Figure 12, the azimuthal director orientation is uniform across the display, but the tilt angle of the posts varies, which may provide a greyscale.

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